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SIMPLER J_{Ic} TEST AND DATA ANALYSIS PROCEDURES FOR HIGH STRENGTH STEELS

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13. ABSTRACT *(Maximum 200 words)*

Tests of five medium and high strength steels were used to investigate some prospective simplifications in J_{Ic} test and data analysis procedures. Three-point bend specimens with material strengths of 500 to 1500 MPa and nominal thickness of 10 mm were tested at room temperature. The investigation included (1) J_{Ic} tests using measured crack-mouth displacement to calculate load-line displacement based on an expression that relates the two displacements; (2) a simple zero-point adjustment for J versus Δa curves, whereby certain intermediate Δa values are shifted to the blunting line to correct for errors at low values of Δa; and (3) a comparison of Δa and J_{Ic} results from the load-drop method, which gives a simple measure of crack growth after maximum load, with results from the usual unloading compliance method. The various results and comparisons are discussed in relation to their usefulness as a general J_{Ic} test procedure for a variety of materials, or a limited use test for certain materials. Two specific test and data analysis procedures are proposed for general use in J_{Ic} testing, as follows:

(1) A new expression is described that calculates load-line displacement for the bend specimen from measured crack-mouth displacement, for a range of a/W values and strain-hardening exponents. The expression makes possible a single-displacement unloading compliance J_{Ic} test for the bend specimen, using a single, standard, crack-mouth clip gage.

(2) A simple zero-shift procedure is proposed for general use with J_{Ic} tests and for addition to ASTM Method E-813. The procedure adjusts the zero point of Δa so that on average the Δa values lie on the blunting line over the J-range of 20 to 60 percent of the provisional fracture toughness, J_Q. The adjustment calculations can be done with a calculator or a few lines of computer code.

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J-Integral Fracture Toughness, Fracture Mechanics, High Strength Steel, Crack-Mouth Displacement, Unloading Compliance, Three-point Bend Specimen

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TABLE OF CONTENTS

TABLES

LIST OF ILLUSTRATIONS

INTRODUCTION

J-integral fracture toughness test procedures use two basic specimen configurations, the pin-loaded compact and the three-point bend. The bend configuration is the simpler, but its use is complicated by the fact that the load-line displacement measurement desired for calculation of applied J is not easy to obtain in an unadulterated form. The measured load-line displacement often contains unwanted components, such as displacements due to elastic deflection or brinelling of loading fixtures, that can cause significant errors in unloading compliance crack growth measurement. A second complication that can occur in J-integral fracture toughness tests is a Δa zero-point offset of the applied J versus crack growth, Δa, curve. Proper test equipment and procedures can minimize this zero offset so that it has no effect on the test result, but until the required test experience is gained by the user, an offset can occur and cause serious problems for all types of J versus Δa tests.

The general goal of this work is to circumvent these two complications in J-integral fracture toughness tests. The relationship between the difficult-to-measure load-line displacement and the easier-to-measure crack-mouth displacement is considered, with the objective of calculating the difficult measurement from the easier one. The zero-point offset problem is addressed by investigating a zero-point adjustment procedure that shifts the J versus Δa data so that an intermediate portion of the data lies, on average, on the blunting line. One other simple method for determining Δa for a J-integral fracture toughness test is considered, the load-drop method, where Δa is determined from the drop in load following maximum load in the test. Each of the above potential simplifications in J-integral fracture toughness test procedure is evaluated by comparison and analysis of the results of J_{Ic} tests from five medium and high strength steels, described in the following section.

MATERIALS AND SPECIMENS

The five steels used and their yield and ultimate tensile strengths are listed in Table 1. The thickness, B, and width, W, of the bend specimen used for each steel are shown, and the type of displacement measurement is noted. Two specimens were tested from a single piece of each of the five materials. The crack-mouth displacement, v, (see Figure 1) measured for three of the steels was the standard clip gage measurement used in ASTM Method E-813 for J_{Ic}, "A Measure of Fracture Toughness." The measurement used with the other two steels was the displacement, δ_L, of the lower edge of the specimen, adjacent to the notch. In prior work (ref 1), J_{Ic} tests using δ_L measurement were successfully performed, by accounting for the offset of the displacement measurement point relative to the loading point. Nevertheless, unwanted displacements of the type mentioned previously can be a problem, as shown by upcoming results.

The chemical composition of the steels is listed in Table 2. The significant variation in chemical composition, combined with the variation in material strengths shown in Table 1, is expected to provide a wide range of fracture toughness behavior and thus a good check on the test procedures under consideration.

RESULTS AND ANALYSIS

An overview of the J-integral fracture toughness results can be seen from a plot of representative J versus Δa results in Figure 2. Note that some of the data points are omitted and lines have been drawn through the remaining data, both for clarity of presentation. One feature of the data that relates to upcoming discussion is the apparent negative crack growth near the beginning of the curve for the 4335 steel results. This may be the result of spurious displacements mixing with the lower edge load-line displacement for the 4335 specimens; the same effect was noted with the A723 steel specimens, which also used lower-edge displacement. The device used to measure the lower-edge displacement accepted a standard clip gage, but it had additional moving parts that may have introduced unwanted displacements. Of course, it is always better to eliminate the cause of the problem, but since the tests were already performed, an attempt was made to circumvent the problem, as follows.

Relationship Between Load-Line and Crack-Mouth Displacement

Kirk and Hackett (ref 2) considered the relationship between load-line and crack-mouth displacement for the purpose of improving J-integral test procedures. They obtained consistent results for the case of large plastic displacements. However, it would be desirable to consider both the predominantly elastic and predominantly plastic cases. It is straightforward to obtain the relationship between the elastic load-line and crack-mouth displacements directly from the expressions summarized in ASTM Method E-813. The dimensionless elastic load-line displacement, $\delta EB/P$, as a function of relative crack length, α, is (ref 3)

$$\delta EB/P = [(S/W)/(1-\alpha)]^2 f_1(\alpha)$$

$$f_1(\alpha) = 1.193 - 1.980\,\alpha + 4.478\,\alpha^2 - 4.443\,\alpha^3 + 1.739\,\alpha^4$$

$$\text{for } 0 \le \alpha \le 1 \tag{1}$$

where E is elastic modulus, $\alpha = a/W$, and the other parameters are defined in Figure 1. The dimensionless elastic crack-mouth displacement, vEB/P, is (ref 4)

$$vEB/P = 6\alpha\,(S/W)\,f_2(\alpha)$$

$$f_2(\alpha) = 0.76 - 2.28\,\alpha + 3.87\,\alpha^2 - 2.04\,\alpha^3 + 0.66/(1-\alpha)^2$$

$$\text{for } 0 \le \alpha \le 1 \tag{2}$$

Calculating v/δ from Eqs. (1) and (2) and fitting a polynomial to the result gives an elastic expression for the ratio v/δ

$$v/\delta = +\,1.718\,\alpha - 1.302\,\alpha^2 + 1.039\,\alpha^3 - 0.452\,\alpha^4$$

$$\text{for } 0 \le \alpha \le 1 \tag{3}$$

This expression is shown in Figure 3 for comparison with the more useful analogous plastic results, determined in the following paragraph. The dimensionless ratio calculated from Eq. (3) fits the values calculated directly from Eqs. (1) and (2) within 0.002 for the entire range of a/W.

Wu, Mai, and Cotterell (ref 5) provided plastic rotation factors, r_P, for three-point bend specimens of various Ramberg-Osgood power law strain-hardening materials, based on numerical results from the literature. They also gave the following expression, based on plane geometry, that relates r_P to $(v/\delta)_{CR}$, the plastic v/δ ratio due to the presence of the crack:

$$r_P = [(v/\delta)_{CR} - \alpha] \,/\, [1-\alpha] \tag{4}$$

However, an expression is needed that relates r_P to the total v/δ ratio, so that the ratio can be used to determine δ from the total measured v in a test. Such an expression can be obtained by noting that the total load-line displacement is the sum of the displacement of the specimen due to the crack and that with no crack, $\delta \;\; \delta_{CR} + \delta_{NC}$, and defining δ_{CR} and δ_{NC} in terms of v, as follows. First,

$$\delta_{CR} = v \,/\, [\alpha + r_P(1-\alpha)] \tag{5}$$

obtained directly from Eq. (4). δ_{NC} for a beam in bending is (ref 3)

$$\delta_{NC} = [P/EB]\ [S^3/4W^3] \tag{6}$$

Combining Eqs. (6) and (2), in order to write δ_{NC} in terms of v, gives

$$\delta_{NC} = v\ (S/W)^2 / 24\ \alpha\ f_2(\alpha) \tag{7}$$

where $f_2(\alpha)$ is from Eq. (2). Combining Eqs. (5) and (7) gives the desired expression for total elastic-plastic load-line displacement in terms of crack-mouth displacement for the bend specimen with S/W = 4, including effects of power law strain-hardening materials via the plastic rotation factor, r_p. The expression is

$$\delta/v = 1 / [\alpha + r_p(1-\alpha)] + 2 / [3\ \alpha f_2(\alpha)]$$

$$\text{for } 0 \leq \alpha \leq 1 \tag{8}$$

Equation 8 was used to calculate v/δ ratios based on r_p values from Reference 5; the inverse of Eq. (8) was used to avoid large numbers for small cracks. Recent work by Kirk and Dodds (ref 6) also addresses the calculation of J for the bend specimen using crack-mouth displacement and includes plastic rotation factors for power law strain-hardening materials. The r_p values from References 5 and 6 discussed here are listed in Table 3.

The comparison of the plastic v/δ ratio for a range of a/W and strain-hardening exponents, n, with the elastic results discussed earlier is shown in Figure 3. Note the relative insensitivity of the results from both References 5 and 6 to strain-hardening exponents, n; similar results were found and noted by Kirk and Dodds. In general, this insensitivity allows the use of the same J-integral calculation over a range of n. For the approach taken here, it allows the use of a single expression for the ratio v/δ over the commonly encountered range of n. A proposed expression is shown in Figure 3. It was fitted to results from Reference 6 for n = 20, obtained by interpolation of the n = 10 and 50 results. The expression was also fitted to limits of v/δ for α = 0 and 1, which are 0 and 1, respectively. The resulting plastic expression for the ratio v/δ is

$$v/\delta = +\ 1.384\ \alpha - 1.497\ \alpha^2 + 2.339\ \alpha^3 - 1.226\ \alpha^4$$

$$\text{for } 0 \leq \alpha \leq 1 \tag{9}$$

Equation 9 fits the v/δ values at the limits and those from the Reference 6 r_p results within 0.003, for the entire range of α. Equation 9 was used for the tests here in which δ and the associated J were determined from measured values of v. Note in Figure 3 that Eq. (9), although fitted to the Kirk and Dodds results of Reference 6, also gives a reasonable fit to the results of Wu et al. (ref 5). The use of the Reference 6 results for the expression was based on the belief that this work used improved finite element methods compared to the work of Kumar et al. (ref 7), on which the Wu et al. r_p results were based. Recent work of Lee and Bloom (ref 8) tends to confirm this belief. The J-integral calculations for the bend specimen from Reference 8 are significantly different from the Kumar et al. (ref 7) results, particularly for relatively small α and large n.

Kirk and Dodds (ref 6) give a useful expression for estimating n from the ultimate to yield strength ratio, σ_U/σ_L, of the material. Their expression is

$$\sigma_U/\sigma_L = [1/(0.002\ n)^{1/n}] / \exp(1/n) \tag{10}$$

Using Eq. (10) and the material strength data in Table 1, the values of n for the tests here are about 8 to 30, in the range of low sensitivity of J to n discussed earlier. So it is appropriate to use the approach of Eqs. (8) and (9) for the tests here. One further comment is offered on the use of the final expression, Eq. (9), in J-integral testing in general. The expression gives a direct calculation of load-line displacement, δ, (based on the easier measurement, v); this allows the well established ASTM methods for calculating J based on δ to be used with no modification.

Δa Zero Shift for J versus Δa Curves

As noted and discussed in relation to Figure 2, some of the results here were in need of a Δa shift in order to address the problem of negative crack growth. This problem is not uncommon, particularly when nonstandard procedures are used, as was the case with the use of lower edge displacement for some tests here. A proposed Δa zero-shift procedure to address this or other problems that cause an incorrect zero point of the J versus Δa curve, follows. Figures 4 and 5 illustrate one type of zero-shift problem and the fundamental solution suggested, respectively. Figure 4 shows J-Δa data obtained with the unloading compliance procedure of ASTM Method E-813, using lower surface displacements (ref 1); note that much of the data at lower J is to the left of the blunting line and indicates negative crack growth. Shifted data is also shown and will be discussed later. The basic procedure proposed is to apply a zero shift to data as shown in Figure 5, using the accepted zero-shift procedure, which has been applied to tensile stress versus strain plots for decades. The lower nonlinear portion of tensile data is routinely ignored by performing a zero shift, as shown.

A zero shift of the tensile test type can be applied to data such as those in Figure 4 by shifting all data an amount which places, on average, certain mid-range J-Δa data on the blunting line. The range of data used to calculate the amount of shift was selected as 20 to 60 percent of the provisional, nonshifted, J-integral toughness, J_Q. The rationale is that below 0.2 J_Q, test start-up inaccuracies are more likely, and above 0.6 J_Q, the J-Δa data are expected to deviate from the blunting line. If there are no data in the 0.2 to 0.6 J_Q range, a shift can be attempted with the available data, but with careful attention to the above rationale. It should be noted that the zero-shift procedure often requires iteration to account for the different set of J-Δa data that can result from the first shift, but the iteration converges quickly. Five of the ten tests here required iteration, but only one iteration in each case, as described later.

The zero-shift procedure, in equation form, is as follows. The zero-point adjustment, Δa_A, can be calculated as

$$\Delta a_A = \mathrm{SUM}_i[\Delta a_i - (J_i/2\sigma_F)] \; / \; i \tag{11}$$

where i is the number of J-Δa points between 0.2 and 0.6 J_Q and σ_F is the flow stress, $\sigma_F = (\sigma_Y + \sigma_U)/2$. The zero-point adjustment is applied to the data that fall above 0.2 J_Q, as follows.

$$\Delta a = \Delta a_i - \Delta a_A \tag{12}$$

Using the procedure of Eqs. (11) and (12) and repeating the ASTM Method E-813 calculation of J_Q gives a shifted provisional toughness, J_{Qs}, as shown in Figure 4. Note that the position of the early data, once shifted, is more physically believable, that is, generally in agreement with the blunting line.

The significant shift of the results in Figure 4 was required because of a problematic test procedure, as has been discussed. An example of a zero shift of J-Δa data that is more representative of proper test and analysis procedures is shown in Figure 6. The only significant deviation from standard ASTM Method E-813 procedures in these results is the use of the Eqs. (8) and (9) procedure to calculate δ from measured v. (Some

of the J-Δa data was omitted for clarity.) Note in Figure 6 that even before the shift, the early results were in reasonable agreement with the blunting line. The shift was smaller than that in Figure 4, and it improved further the agreement of the data with the blunting line.

A summary of the zero-shift results for each of the five steels and ten specimens tested is shown as Table 4. The J_Q from the usual method with no shift is compared with the value following the shift, J_{Q*}, and the corresponding shift amount, Δa_A, and number of points used to calculate the shift are shown. Five of the ten tests required a second application of the shift procedure of Eqs. (11) and (12) to converge to a constant value of J_{Q*}, the second listed value for these five tests. This second shift corresponded to a different group of data points (between 20 and 60 percent of J_Q) being used to calculate the shift. Note that the two sets of tests using lower surface displacement, A723 and 4335 steel, required significantly larger shifts, another consequence of the adulterated displacement. The largest shift in the tests was 0.142 mm, which is about 0.7 percent of the specimen width. There was no indication that this largest shift caused any inconsistencies in the determination of J_Q.

One other point should be mentioned. The test pair showing the largest difference in J-integral toughness, both before and after shift, was the A723 pair. The reason for this difference is believed to be the use of 20 percent side grooving on A723-2 and no side grooving on A723-1 (or any other test). The net thickness of the side-grooved specimen was accounted for, as described in ASTM Method E-813. Figure 7 shows these test results following the shift; the steeper slope of the J versus Δa curve of the specimen with no side grooves is apparent, as well as the higher toughness.

Load-Drop Compared with Unloading Compliance

These five pairs of data provide a good opportunity to check the load-drop method (ref 9), which was proposed as a simple, approximate method to determine Δa in J-integral fracture testing. In brief summary, by using the expression for limit moment, M_L, for a bend specimen (ref 10),

$$M_L = 0.36\ B\ (W-a)^2\ \sigma_P \qquad (13)$$

the following approximation for Δa can be made:

$$\Delta a = J/2\sigma_P + [W-a_O][1-(P_i/P_{MAX})^{1/2}] \qquad (14)$$

where a_O is the original crack length before any growth and P_i is the load at any point after maximum load, P_{MAX}. The $J/2\sigma_P$ term accounts for the effective "crack growth" associated with blunting as the load increases to P_{MAX}. As can be deduced from Eq. (14), it is an approximation because any crack growth that occurs before P_{MAX} is not accounted for except by the blunting term.

The load-drop procedure of Eq. (14) was used to determine Δa for the ten tests, and they were plotted and evaluated in all other aspects as in ASTM Method E-813. One of the results is plotted in Figure 8, and, like all the results, the provisional toughness using the load-drop Δa values, J_{QL}, is above that using unloading compliance. All of the results are summarized in Table 5. The load-drop result varies from about 10 to 90 percent higher than the unloading compliance result. This indicates that for each of the five materials here there is significant crack growth before maximum load. Another indication that crack growth before maximum load has occurred is that the maximum load is generally below the limit load (based on Eq. (13)), as shown in Table 5. The rationale for this is that when there is sufficient plastic deformation so that $P_{MAX}/P_L = 1$, then crack growth will be delayed until after maximum load, whereas for $P_{MAX}/P_L < 1$, there is less plastic deformation and more chance of crack growth before maximum load.

SUMMARY AND CONCLUSIONS

The relationship between crack-mouth and load-line displacements for the three-point bend specimen has been described over the full range of a/W and a significant range of Ramberg-Osgood strain-hardening exponents. A single polynomial expression was developed that applies to most structural alloys. The expression is suggested for general use in performing J-integral tests with the three-point bend specimen using only crack-mouth displacement measurements. Calculation of load-line displacement can be made using the expression and used directly with the ASTM test procedures for J-integral fracture toughness.

A procedure has been proposed for applying a zero shift of Δa in the plotting and analysis of applied J versus Δa curves. The procedure places mid-range J-Δa data on the blunting line and ignores lower data which can cause an aphysical zero point on a J-Δa curve. Shifted curves for five medium and high strength steels were simply accomplished and made physical sense. The procedure is suggested for addition to ASTM Method E-813 for general use. It can be incorporated into computer-controlled test procedures by addition of a few lines of computer code, or it can be performed with a calculator.

The load-drop method for estimating Δa in J-integral fracture toughness tests has been directly compared with unloading compliance measurements of Δa. The resulting J_Q values were significantly higher using load-drop than those using unloading compliance for each of the five steels. This difference is believed to be caused by crack growth occurring before maximum load in the tests, which is not accounted for in the load-drop method. Therefore, the load-drop method should be limited to materials and test conditions for which crack growth only after maximum load can be assured.

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Table 1. Material and Specimen Data

Type of Steel	Yield Strength (MPa)	Tensile Strength (MPa)	Thickness, B (mm)	Width, W (mm)	Type of Displacement
NiMn	520	710	10.0	20.0	Crack Mouth
D6AC	1030	1120	7.6	15.2	Crack Mouth
A723	1120	1210	10.0	20.0	Lower Edge
4335	1240	1320	10.0	20.0	Lower Edge
1410	1530	1750	10.0	20.0	Crack Mouth

Table 2. Typical Material Compositions
(Weight Percent)

Element	NiMn	D6AC	A723	4335	1410
Chromium	0.10	1.09	0.99	0.82	1.94
Molybdenum	0.12	0.95	0.57	0.44	1.02
Manganese	0.68	0.69	0.62	0.51	0.02
Nickel	2.74	0.44	3.04	1.95	10.20
Cobalt	--	--	--	--	13.70
Carbon	0.41	0.50	0.30	0.34	0.16
Vanadium	0.06	0.13	0.11	0.08	--
Phosphorus	0.032	0.013	0.010	0.010	0.004
Sulfur	0.033	0.004	0.007	0.007	0.001

Table 3. Plastic Rotation Factors, r_Y, from the Literature for the Three-Point Bend Specimen

Wu, Mai, and Cotterell (Ref 5)			Kirk and Dodds (Ref 6)			
a/W	n = 5	n = 20	a/W	n = 5	n = 10	n = 50
0.250	0.367	0.432	0.05	0.053	0.089	0.142
0.375	0.418	0.423	0.15	0.171	0.261	0.404
0.500	0.438	0.435	0.25	0.240	0.352	0.431
0.625	0.457	0.441	0.50	0.343	0.380	0.426
0.750	0.487	0.528	0.70	0.341	0.395	0.398
0.875	0.514	0.556				

Table 4. Summary of J_{Ic} Zero-Shift Results

Test	J_Q; E-813 Method (N/mm)	J_{Q*}; with Zero Shift (N/mm)	Amount of Shift (mm)	Number of Data Used for Shift
NiMn-1	149	144	+0.014	9
		143	+0.017	8
NiMn-2	139	146	-0.024	7
		146	-0.030	8
D6AC-1	108	107	+0.002	3
D6AC-2	116	119	-0.011	4
		121	-0.018	3
A723-1	281	248	+0.046	6
A723-2	230	208	+0.109	6
4335-1	88	83	+0.034	5
4335-2	88	77	+0.142	6
		79	+0.124	6
1410-1	212	212	-0.002	8
		213	-0.005	9
1410-2	207	205	+0.010	9

Table 5. Summary of Load-Drop J_{Ic} Results

Specimen	J_{QS}; E-813 with Zero Shift (N/mm)	J_{QL}; E-813 Using Load-Drop Δa (N/mm)	P_{MAX}/P_{LIMIT}
NiMn-1	143	278	0.89
NiMn-2	146	288	0.88
D6AC-1	107	183	0.82
D6AC-2	121	177	0.77
A723-1	248	277	0.80
A723-2	208	288	0.99
4335-1	83	134	0.67
4335-2	79	108	0.61
1410-1	213	279	0.84
1410-2	205	275	0.85

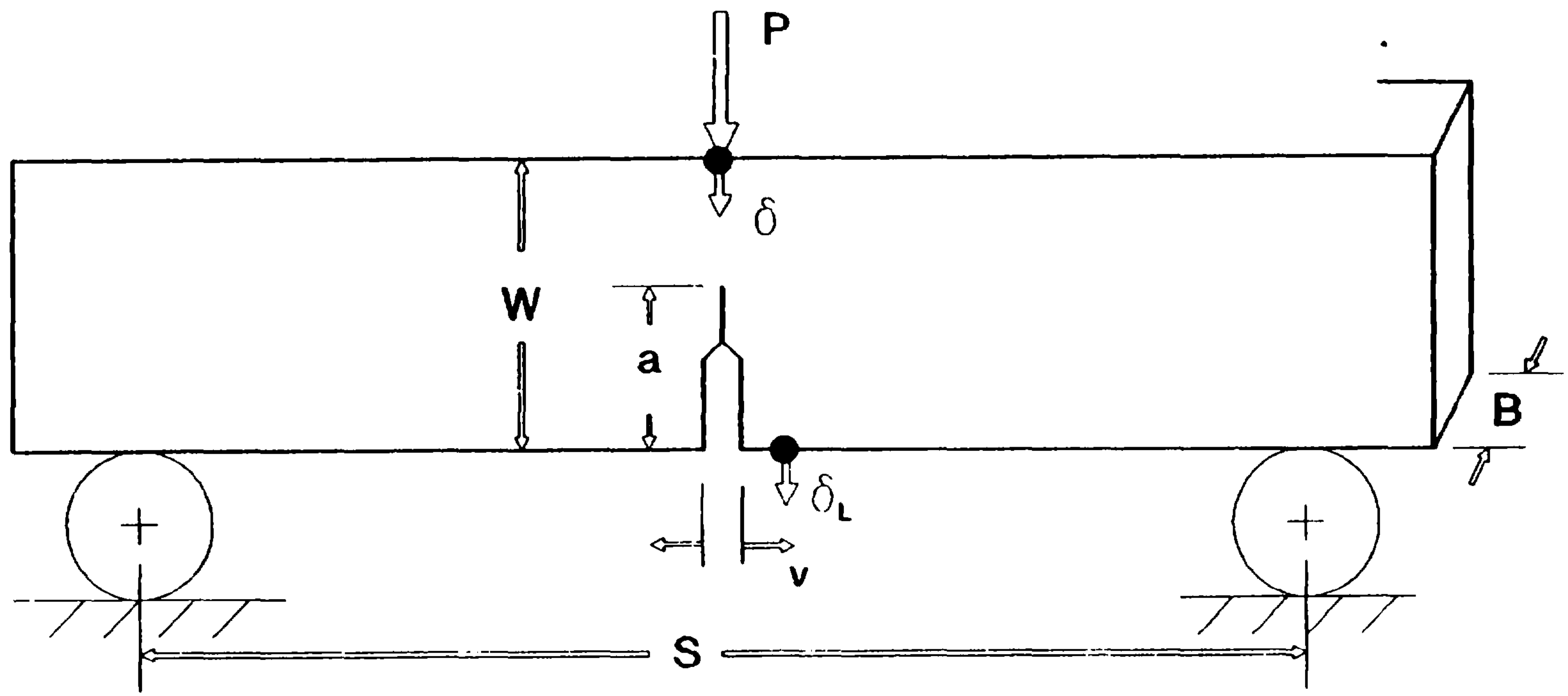

Figure 1
Bend Specimen Configuration Showing
Nomenclature and Displacements

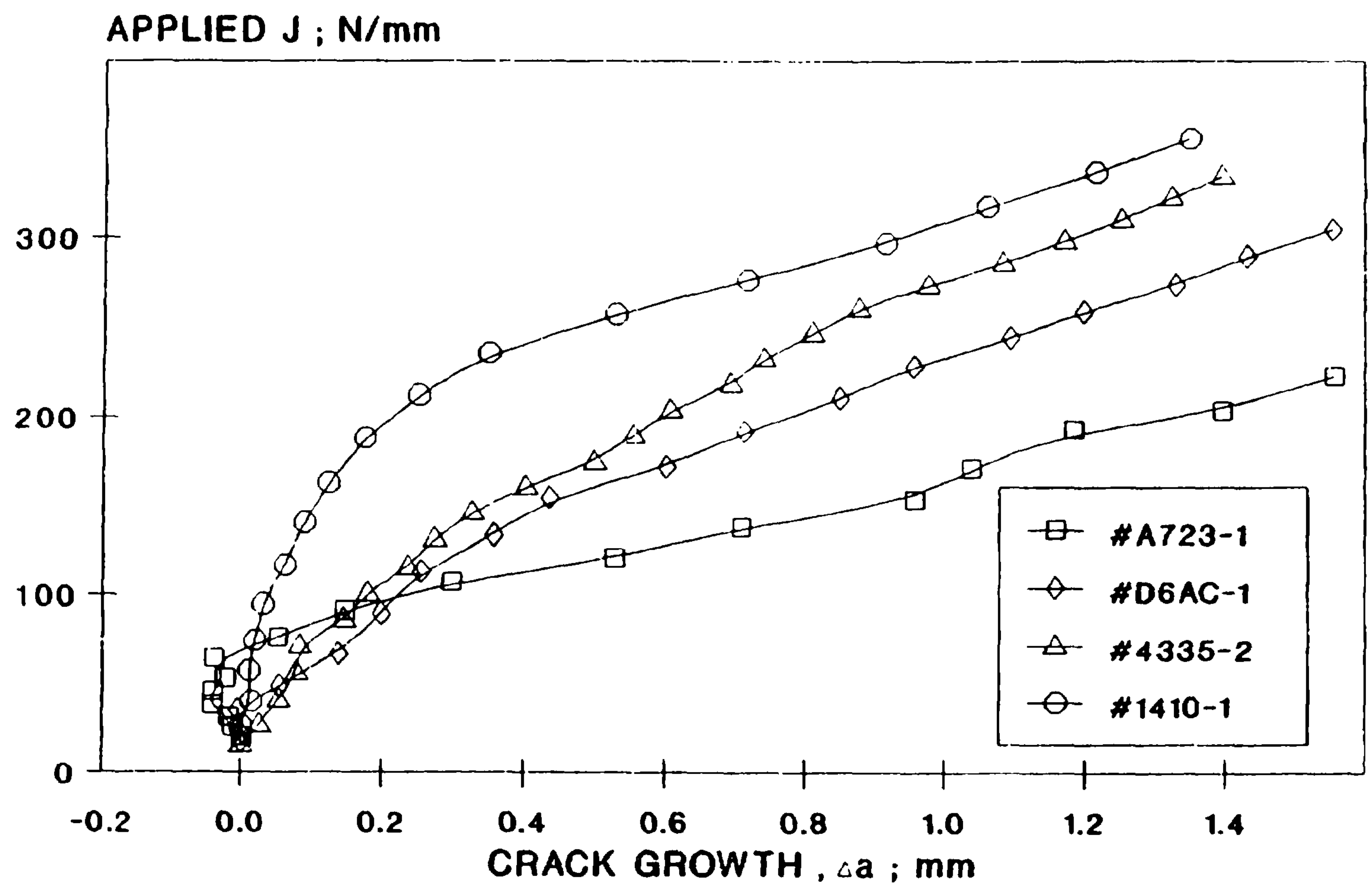

Figure 2
Applied J vs Δa for Four Steels

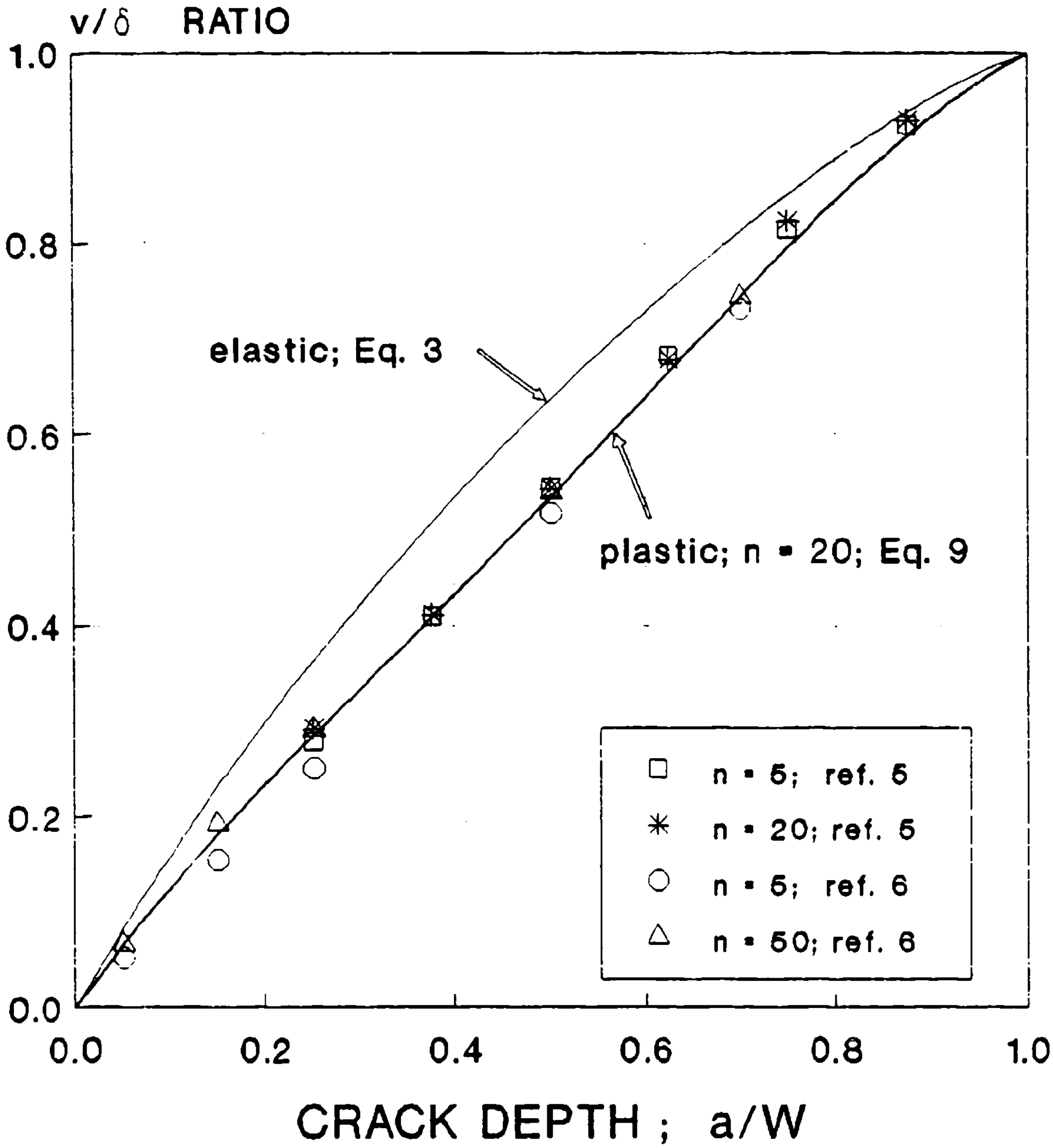

Figure 3
Displacement Results for Three-Point Bend Specimen; Elastic and Plastic

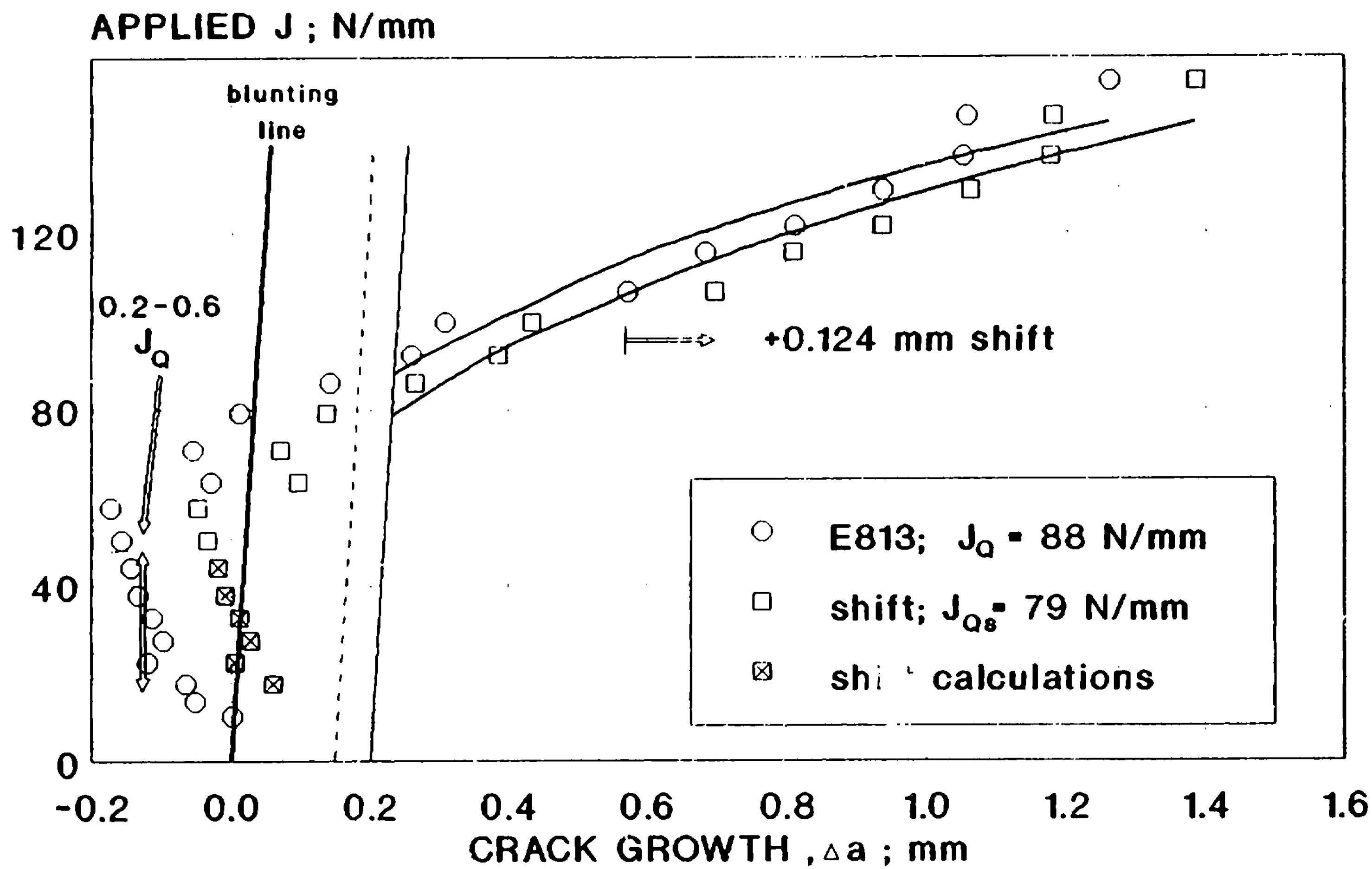

Figure 4
J-Ic by E813 Method and with Zero Shift;
#4335-2, Lower Edge Displacement

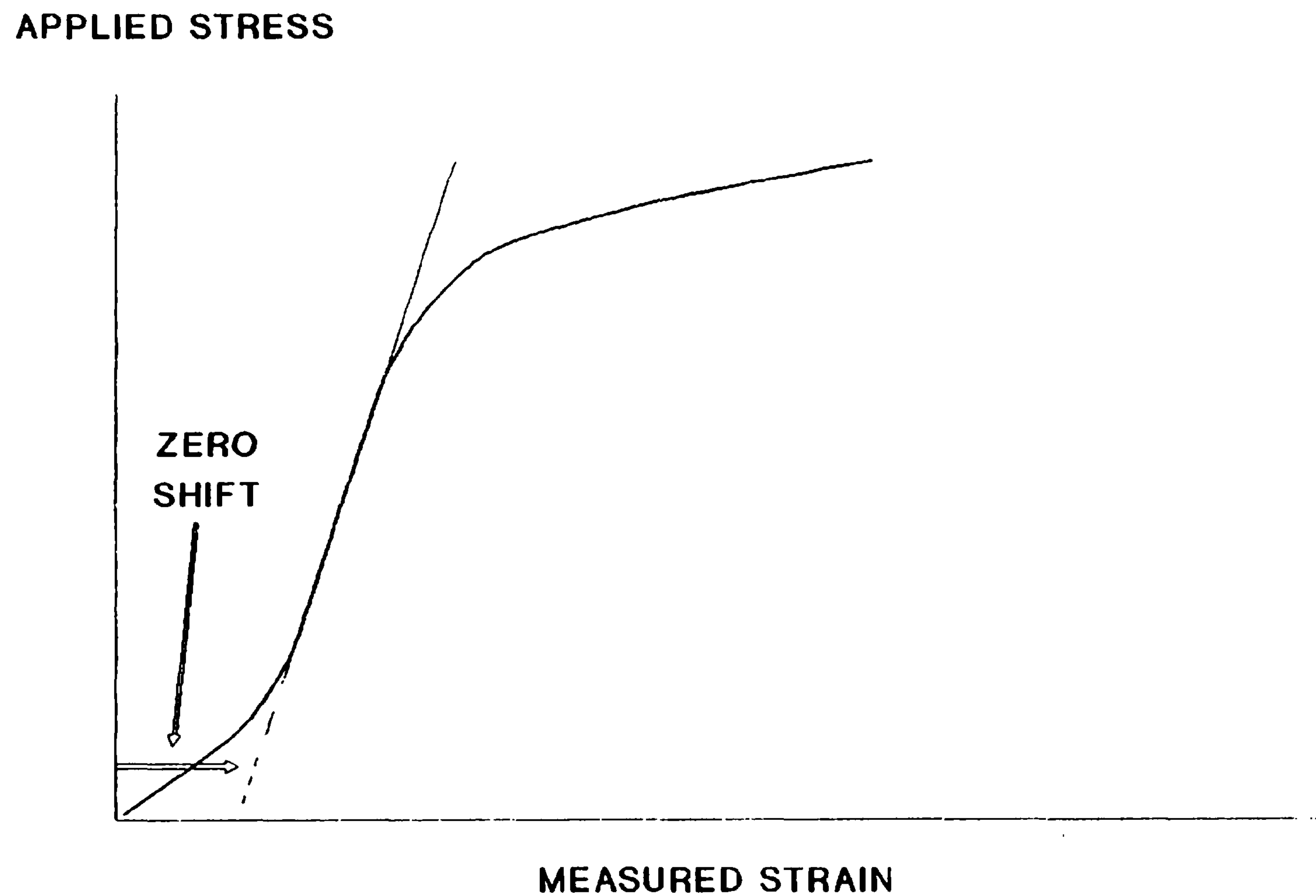

Figure 6
Sketch of a Stress-Strain Plot
with a Zero Shift

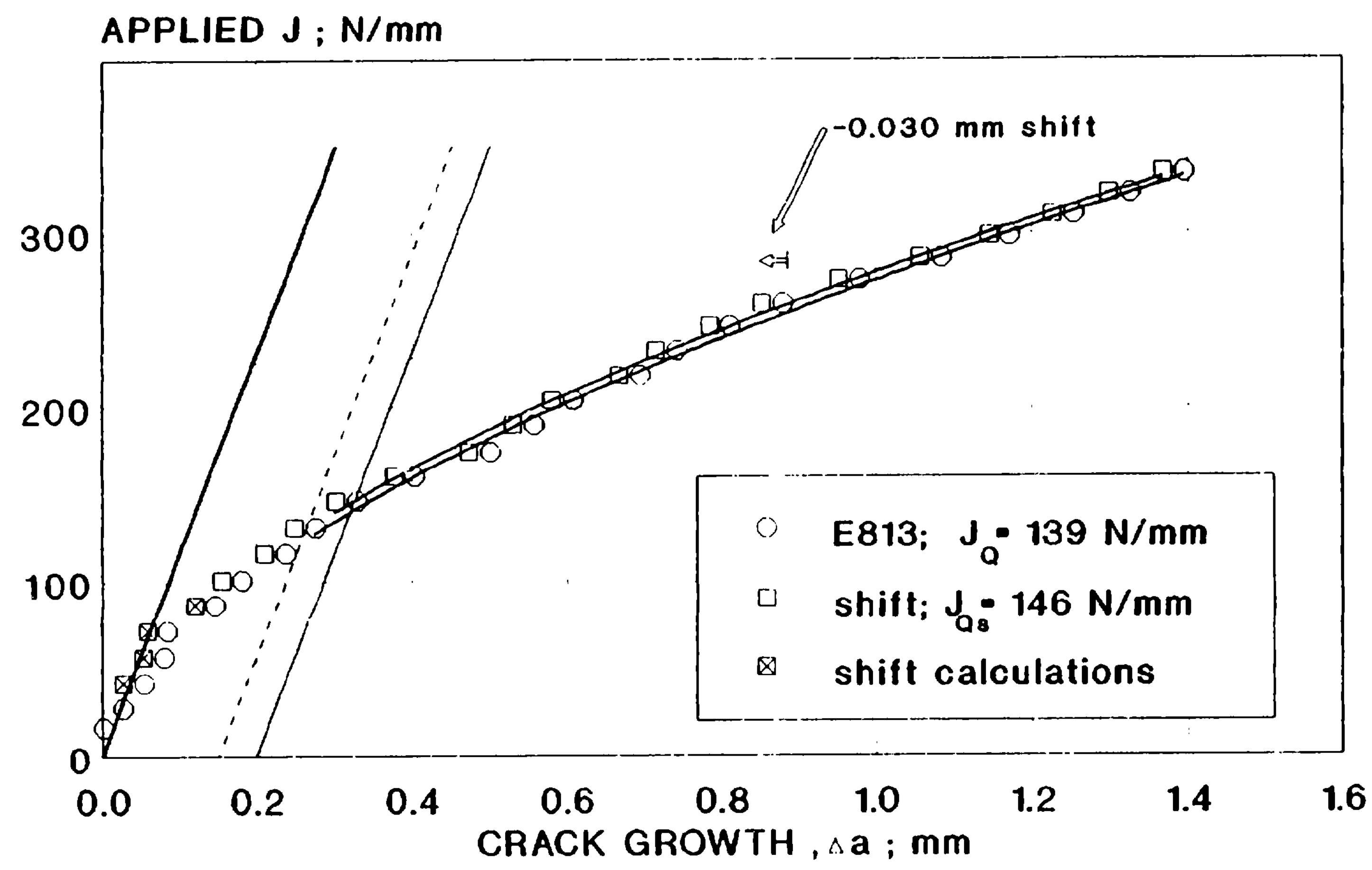

Figure 6
J-Ic by E813 Method and with Zero Shift;
#NiMn-2, Crack Mouth Displacement

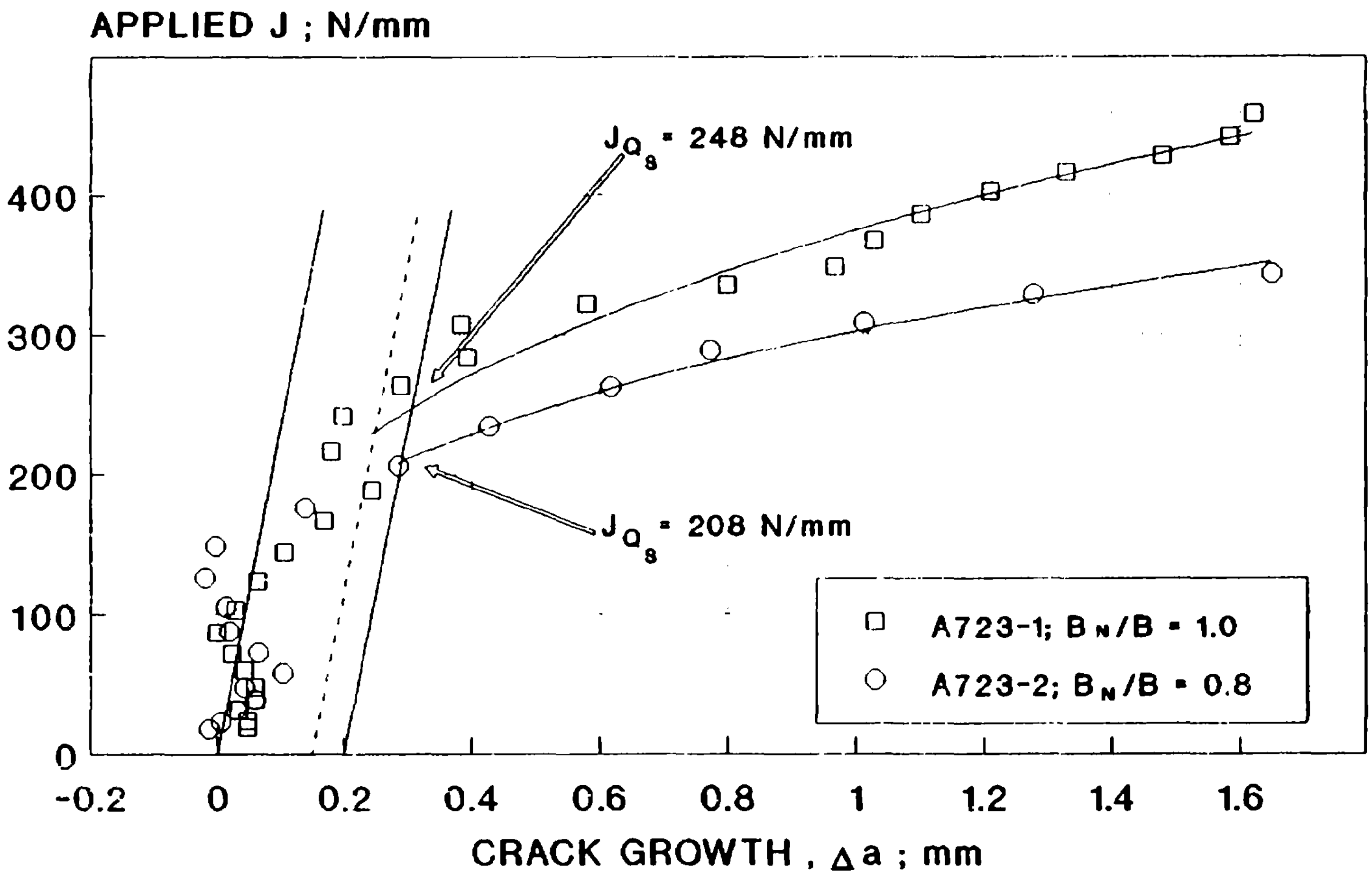

Figure 7
J-Ic by E813 Method with Zero Shift;
#A723-1 and #A723-2

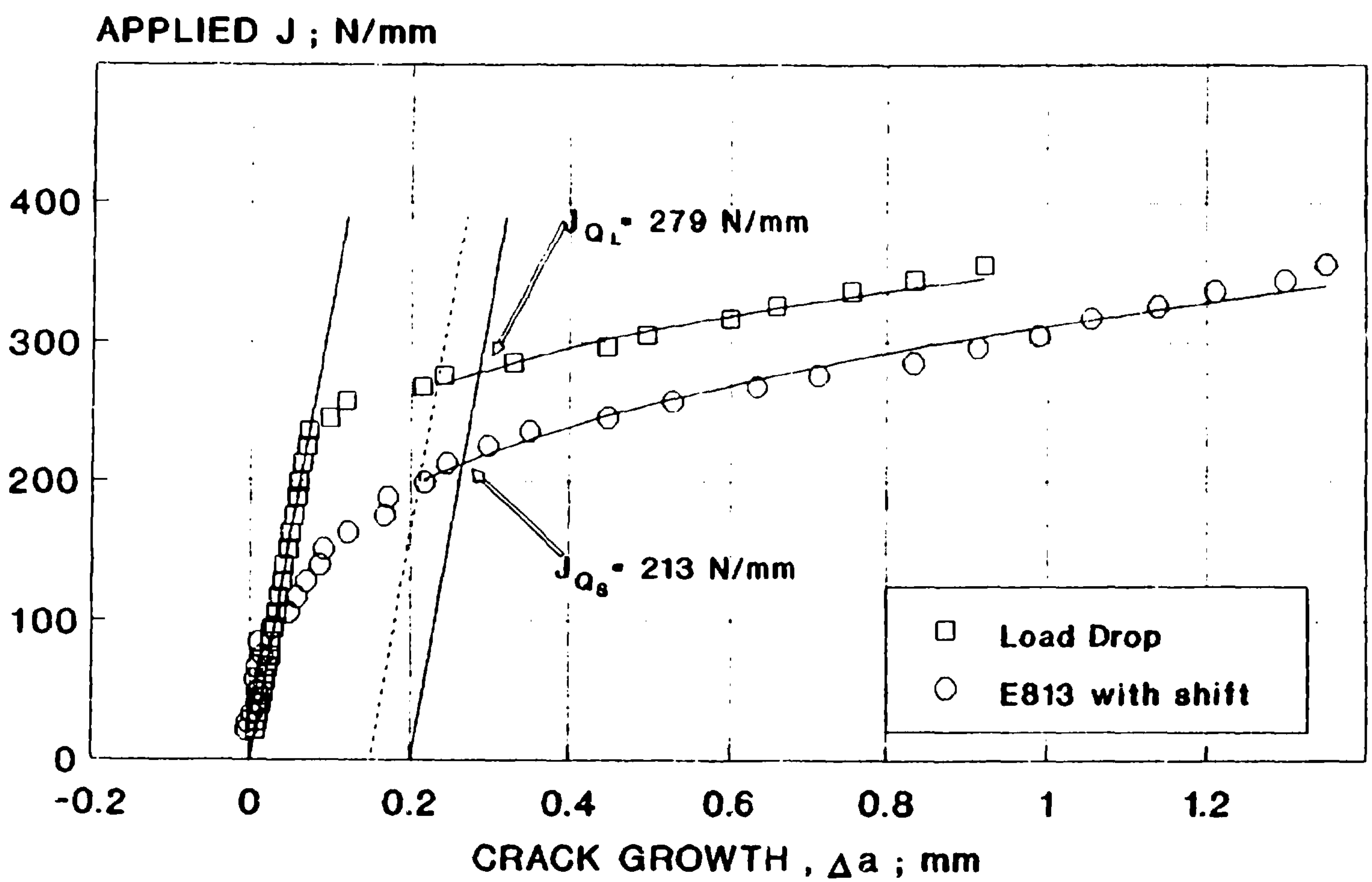

Figure 8
J-Ic by Load Drop and E813 Methods;
#1410-1

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